SEARCH FOR AMBIENT NEUTRALINO DARK MATTER AT ACCELERATOR

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Abstract

We investigate the possibility of using accelarator beam particles to collide with the ambient neutralino dark matter particles in cosmic rays as a way to search for the cold dark matter. We study in detail its inelastic and elastic scattering with the projectile particles at electron-positron colliders and discuss the possible experimental signals and the relevent background.

There is strong evidence for the existence of a large amount of cold dark matter (CDM) in the universe. The leading candidate of the cold dark matter particles in the minimal supersymmetric standard model with R parity is neutralino [1, 2]. The possibility of sneutrino being a candidate of CDM is ruled out unless it as heavy as 17 TeV which is unfavorable in all resonable theories[4, 5].

In the traditional method of directly searching for such CDM SUSY particles, the velocity of the SUSY CDM particles is very small [3], their kinetic energy is not sufficient to cause any inelastic scattering, so that a clear observation would be difficult due to existence of a flood of background trajectories. In this paper we propose a new detection mechanism of neutralino cold dark matter by using the accelarator beam particles to collide

with the ambient neutralino dark matter particles. Namely we use the projectile particles produced in accelerator ($e^{\pm}, p(\bar{p})$ or even γ) to be incident on the dark matter particles. Because most of the cosmic ray particles interact with ordinary matter via electromagnetic processes, they cannot penetrate into the tunnel with high vacuum, but the dark matter particles only participate in "weak" interaction and can come into the tunnel. Concretely, we let the beam (say, e^-) go through a highly vacuumized tunnel while the colliding beam (e^+) is turned off. Once the projectile electrons bombard on neutralinos ($\tilde{\chi}_1^0$), because of the large available energy of e^-, inelastic processes may occur as

$$\tilde{\chi}_1^0 + e^- \to \tilde{\chi}_1^- + \nu_e. \tag{1}$$

The charged SUSY particles $\tilde{\chi}_1^-$ would make trajectories in detector with magnetic field. Because they are much heavier than proton and pion etc. ordinary particles, they can be identified easily from background products. There are also elastic processes

$$\tilde{\chi}_1^0 + e^- \to \tilde{\chi}_1^0 + e^-, \quad \nu_e + e^-, \tag{2}$$

where the projectile electron declines from its beam direction. However, this process might be smeared with the background effect such as

$$n + e^- \to n + e^-,$$

where n is the nucleon left in the tunnel, even though it is highly vacuumized. We will discuss the background problem again later in this letter.

The density of cold dark matter in our ambient universe has been estimated [6]. There have also been many theoretical works concerning the SUSY relic density after the Big Bang [7]. Thus we can immediately evaluate the flux of the SUSY cold dark matter [8]. The observed event number of the suggested reaction can be obtained as

$$N = \rho_{DM} \cdot \rho_{beam} \cdot |\vec{v}_{rel}| \sigma S \cdot l \cdot t = \rho_{DM} \cdot \frac{1}{2} L \sigma S \cdot l \cdot t, \tag{3}$$

where ρ_{DM}, ρ_{beam} are the densities of dark matter and beam particles respectively, $|\vec{v}_{rel}|$ is their relative velocity, σ is the cross section of the reaction, S is the cross section of the beam, l is the length of the available detection region, t is the time duration for measurement. Since the velocity of the coming SUSY particles is much lower than that of the beam particle, $\rho_{beam}|\vec{v}_{rel}| \sim L/2$ where L is the named luminosity.

In 1972, a peculiar event of heavy cosmic ray particle was observed in the cloudy chamber of the Yunan Cosmic Ray Station (YCRS) [9]. Recently, the event was re-analyzed [10] and it is identified as that a heavy neutral particle C^0 came in and bombarded on a proton to produce a heavy charged particle C^+ as well as a proton and π^-. Their analysis confirmed that the mass of the heavy neutral cosmic ray particle C^0 is greater than 43 GeV and the mass difference

$$\Delta M = M_{C^+} - M_{C^0} < 0.270 \text{ GeV}.$$

If taking this result seriously, one would be tempted to conclude that the coming neutral C^0 is a SUSY dark matter particle $\tilde{\chi}_1^0$ and the produced heavy charged particle is $\tilde{\chi}_1^+$ accordingly. In this case, the available energy of the Beijing Electron-Positron Collider (BEPC) is sufficient to cause an inelastic scattering where the projectile particle e^- of 2 GeV hits the coming $\tilde{\chi}_1^0$ to produce $\tilde{\chi}_1^-$. If the mass difference of $\tilde{\chi}^\pm$ and $\tilde{\chi}^0$ is as large as a few tens GeV, the BEPC energy is not sufficient, and one needs to invoke machines with higher energy, such as, LEP or hadron colliders. In this paper we will take $\Delta M < 1$ GeV for a detail study, and then we will briefly give a general discussion on the case for larger ΔM.

In calculation of the cross section σ in eqs.(1), (2) and (3) without losing generality we assume that only one generation sfermion is light and one can neglect the sfermion mixing among different generations. The mass matrices of neutralinos and charginos can be found in Ref[1]. For the mixing of the first generation slepton (right and left fields), we have

$$M_{\tilde{e}}^2 = \begin{pmatrix} -\frac{e^2(v_1^2-v_2^2)(1-2c_w^2)}{8s_w c_w} + M_e^2 + M_L^2 & \frac{1}{\sqrt{2}}\left(\sqrt{2}M_e\mu + v_1 h_{s_l}^1\right) \\ \frac{1}{\sqrt{2}}\left(\sqrt{2}M_e\mu + v_1 h_{s_l}^1\right) & \frac{e^2(v_1^2-v_2^2)}{4c_w^2} + M_e^2 + M_R^2 \end{pmatrix}. \tag{4}$$

The mixing matrix $Z_{\tilde{e}}$ is defined as

$$Z_{\tilde{e}}^\dagger M_{\tilde{e}}^2 Z_{\tilde{e}} = diag(M_{\tilde{e}_1}^2, M_{\tilde{e}_2}^2). \tag{5}$$

The mass of the electron-sneutrino is:

$$M_{\tilde{\nu}_e}^2 = M_L^2 - \frac{e^2(v_1^2-v_2^2)}{8s_w^2 c_w^2}. \tag{6}$$

At tree level, the squared mass, $M_{H_1^0}^2$, of the light Higgs boson has an upper bound which is given by $M_Z^2 \cos^2 2\beta$. This is already below the experimental lower bound of LEP2[11]. However, radiative corrections can raise the upper bound on $M_{H_1^0}^2$ dramatically[12]. The dominant contribution is

$$\triangle M_{H_1^0}^2 = \frac{3M_t^4}{2\pi^2 v^2} \ln \frac{M_{\tilde{t}}^2}{M_t^2}, \tag{7}$$

where M_t is the top quark mass and $M_{\tilde{t}}$ the top-squark mass. In our numerical calculation, we take the correction into account.

When the kinematics is permissive, several inelastic reactions such as $e^- + \tilde{\chi}_1^0 \to \tilde{\nu}_e + W^-(H_1^-)$, $e^- + \tilde{\chi}_1^0 \to \tilde{e}_i^- + Z^0(H^0, A^0)$ ($i = 1, 2$) etc. can occur. For the moment we consider only inelastic channels $e^- + \tilde{\chi}_1^0 \to \tilde{\chi}_1^- + \nu_e$ and as well the elastic processes $e^- + \tilde{\chi}_1^0 \to e^- + \tilde{\chi}_1^0$. For the channel $e^- + \tilde{\chi}_1^0 \to \tilde{\chi}_1^- + \nu_e$, the amplitudes are given as

$$\mathcal{M}_{\tilde{e}_i^-}^s = -\frac{i}{s - M_{\tilde{e}_i^-}^2} \sum_{\sigma_1\sigma_2} A_{\sigma_1}^{(1)} B_{\sigma_2}^{(1)} \bar{v}(p_2)\omega_{\sigma_1} u(p_1)\bar{u}(p_4)\omega_{\sigma_2} v(p_3),$$

$$\mathcal{M}_W^u = -\frac{i}{u - M_W^2} \frac{e^2}{2s_w^2} \sum_\sigma C_\sigma^{(1)} v^T(p_3) C^{-1} \gamma_\mu \omega_- u(p_1) \bar{u}(p_4) \gamma^\mu \omega_\sigma C \bar{v}^T(p_2)$$

$$= -\frac{i}{u - M_W^2} \frac{e^2}{2s_w^2} \sum_\sigma C_\sigma^{(1)} \bar{u}(p_3) \gamma_\mu \omega_- u(p_1) \bar{u}(p_4) \gamma^\mu \omega_\sigma u(p_2),$$

$$\mathcal{M}_{\tilde{\nu}_e}^t = \frac{-i}{t - M_{\tilde{\nu}_e}^2} \sum_{\sigma_1 \sigma_2} D_{\sigma_1}^{(1)} E_{\sigma_2}^{(2)} \bar{v}(p_2) \omega_{\sigma_1} v(p_3) \bar{u}(p_4) \omega_{\sigma_2} u(p_1), \tag{8}$$

where the couplings are

$$A_-^{(1)} = \frac{e}{\sqrt{2} s_w c_w} Z_{\tilde{e}}^{1i} (Z_N^{11} s_w + Z_N^{21} c_w),$$

$$A_+^{(1)} = -\frac{\sqrt{2} e}{c_w} Z_{\tilde{e}}^{2i} Z_N^{11*},$$

$$B_-^{(1)} = 0,$$

$$B_+^{(1)} = -\frac{e}{s_w} Z_{\tilde{e}}^{1i*} Z_-^{1j*},$$

$$C_-^{(1)} = Z_N^{21} Z_+^{1j*} - \frac{Z_N^{41} Z_+^{2j*}}{\sqrt{2}},$$

$$C_+^{(1)} = Z_N^{21*} Z_-^{1j} + \frac{Z_N^{3i*} Z_-^{2j}}{\sqrt{2}},$$

$$D_-^{(1)} = \frac{e}{\sqrt{2} s_w c_w} (Z_N^{11} s_w - Z_N^{21} c_w),$$

$$D_+^{(1)} = 0,$$

$$E_-^{(1)} = -\frac{e}{s_w} Z_+^{1j},$$

$$E_+^{(1)} = 0. \tag{9}$$

Z_N, Z_+, Z_- are defined in [1] and $Z_{\tilde{e}}$ is given in (5).

The amplitudes for $e^- + \tilde{\chi}_1^0 \to e^- + \tilde{\chi}_i^0$ (when i=1, it is the elastic scattering case) are

$$\mathcal{M}_{\tilde{e}_j^-}^s = -\frac{i}{s - M_{\tilde{e}_j^-}^2} \sum_{\sigma_1 \sigma_2} A_{\sigma_1}^{(2)} B_{\sigma_2}^{(2)} \bar{v}(p_2) \omega_{\sigma_1} u(p_1) \bar{u}(p_3) \omega_{\sigma_2} v(p_4),$$

$$\mathcal{M}_{Z^0}^t = \frac{i}{t - M_Z^2} \sum_{\sigma_1 \sigma_2} C_{\sigma_1}^{(2)} D_{\sigma_2}^{(2)} \bar{u}(p_3) \gamma_\mu \omega_{\sigma_1} u(p_1) \bar{v}(p_2) \gamma^\mu \omega_{\sigma_2} v(p_4),$$

$$\mathcal{M}_{\tilde{e}_j^-}^u = -\frac{i}{u - M_{\tilde{e}_j^-}^2} \sum_{\sigma_1 \sigma_2} E_{\sigma_1}^{(2)} F_{\sigma_2}^{(2)} \bar{u}(p_3) \omega_{\sigma_1} u(p_2) \bar{u}(p_4) \omega_{\sigma_2} u(p_1). \tag{10}$$

The couplings are written as

$$A_-^{(2)} = \frac{e}{\sqrt{2} s_w c_w} Z_{\tilde{e}}^{1j} (Z_N^{11} s_w + Z_N^{21} c_w),$$

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$$A_+^{(2)} = -\frac{\sqrt{2}e}{c_w} Z_{\tilde{e}}^{2j} Z_N^{11*},$$

$$B_-^{(2)} = -\frac{\sqrt{2}e}{c_w} Z_{\tilde{e}}^{2j*} Z_N^{1i},$$

$$B_+^{(2)} = \frac{e}{\sqrt{2}s_w c_w} Z_{\tilde{e}}^{1j*} (Z_N^{1i*} s_w + Z_N^{2i*} c_w),$$

$$C_-^{(2)} = \frac{e}{s_w c_w} (\frac{1}{2} - s_w^2),$$

$$C_+^{(2)} = -\frac{e s_w}{c_w},$$

$$D_-^{(2)} = \frac{e}{2 s_w c_w} Z_N^{41*} Z_N^{4i},$$

$$D_+^{(2)} = \frac{e}{2 s_w c_w} Z_N^{31} Z_N^{3i*},$$

$$E_-^{(2)} = -\frac{\sqrt{2}e}{c_w} Z_{\tilde{e}}^{2j*} Z_N^{11},$$

$$E_+^{(2)} = \frac{e}{\sqrt{2}s_w c_w} Z_{\tilde{e}}^{1j} (Z_N^{11*} s_w + Z_N^{21*} c_w),$$

$$F_-^{(2)} = \frac{e}{\sqrt{2}s_w c_w} Z_{\tilde{e}}^{1j*} (Z_N^{1i} s_w + Z_N^{2i} c_w),$$

$$F_+^{(2)} = -\frac{\sqrt{2}e}{c_w} Z_{\tilde{e}}^{2j} Z_N^{1i*}. \tag{11}$$

With the amplitude, we can easily obtain the cross sections by integrating over the phase space of final states. It is noted that we carry out all the calculations in the laboratory frame because the velocity of the heavy dark matter particles is very small compared to that of the projectile beam particles.

In our numerical calculations, we take $\alpha = 1/128.8, M_Z = 91.12$ GeV, $M_W = 80.22$ GeV and first assume that $M_{\tilde{\chi}^-} - M_{\tilde{\chi}_1^0}$ is about 1 GeV. We will also present the results for larger mass difference later. For $e^- + \tilde{\chi}_1^0 \rightarrow \tilde{\chi}_1^- + \nu_e$ we take the SUSY parameters as $\tan\beta = 5, M_{\tilde{\chi}_2^-} = 200$ GeV. In the propagators we choose the typical values for the SUSY particle pole masses as $M_{\tilde{e}_1} = 110$ GeV $M_{\tilde{e}_2} = 200$ GeV, $M_{\tilde{\nu}_e} = 110$ GeV. For the Higgs masses, we have $M_{H_1^0} = 110$ GeV, $M_{H_2^0} = 300$ GeV and $M_{A^0} = 110$ GeV which are commonly adopted in literatures.

In the computations, we consider three possible masses of $\tilde{\chi}_1^0$ as 40 GeV, 50 GeV, and 80 GeV.

We find that the cross section of $e^- + \tilde{\chi}_1^0 \rightarrow \tilde{\chi}_1^- + \nu_e$ is of order 100μb, which is the typical value for the weak interactions. We tabulate event numbers of inelastic process $e^- + \tilde{\chi}_1^0 \rightarrow \tilde{\chi}_1^- + \nu_e$ for luminosities and energies of various $e^+ e^-$ colliders in Table 1.

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	$c - \tau$ factory	BEPC	VEPP-4M	CESR	KEKB	PEP-II	LEP
$M_{\tilde{\chi}_1^0} = 40$ $M_{\tilde{\chi}_1^-} = 41$	800	20	250	392	375	850	4950
$M_{\tilde{\chi}_1^0} = 50$ $M_{\tilde{\chi}_1^-} = 51$	1400	40	380	538	625	1410	1300
$M_{\tilde{\chi}_1^0} = 80$ $M_{\tilde{\chi}_1^-} = 81$	16350	490	11830	18676	51875	32032	26850
$M_{\tilde{\chi}_1^0} = 40$ $M_{\tilde{\chi}_1^-} = 60$	−	−	−	−	−	−	2106
$M_{\tilde{\chi}_1^0} = 40$ $M_{\tilde{\chi}_1^-} = 90$	−	−	−	−	−	−	2711

Table 1

The estimated event number for $e^- + \tilde{\chi}_1^0 \to \tilde{\chi}_1^- + \nu_e$. Here the length of detection region l is taken as 1 m and the masses are in GeV. In the third row, the number is unreasonably large and it is because of the pole effect of the propagator and related to the chosen parameters. The last two rows correspond to larger $\Delta M = 20$, 50 GeV, and only the LEP beam energy is capable of making such inelastic process.

For the elastic processes $e^- + \tilde{\chi}_1^0 \to \tilde{\chi}_1^0 + e^-$, we evaluated the cross sections in terms of the parameters introduced above and obtain that the event number of such reactions at the BEPC luminosity and energy is still about 50 per year.

Experimentally we expect to observe inelastic scattering between neutralino and the beam particles at e^+e^- machines. Because all SUSY particles are much heavier than ordinary SM particles, the trajectories of charged SUSY and SM particles can be easily distinguished in a strong magnetic field. At lower beam energies, such as BEPC, the kinetic energy of the produced chargino is relatively small, so that one can easily detect them.

The third row of Table 1 show very large number of events, the reason is due to the pole of the propagator. But unless the matching happens to occur this way, it is not the case. So we do not take such large numbers seriously, of course, if the beam energy can be adjusted freely in a wide range, the threshold effects might manifest, but the possibility in practice is slim.

Now let us turn to study the elastic processes where the background may contaminate the situation. The observation is based on measuring the electrons scattered from the SUSY dark matter particles in $e^- + \tilde{\chi}_1^0 \to e^- + \tilde{\chi}_1^0$. The background is from the electrons scattered from nucleons of the remnant atmosphere in the vacuumized tunnel $e^- + n \to e^- + n$. At lower energies, the cross section of scattering can be easily computed and the

amplitude is

$$\mathcal{M} = \frac{G_F}{2\sqrt{2}} \bar{n}\gamma_\mu[(-1 + \frac{4}{3}\sin^2\theta_W) + \gamma_5]n\bar{e}[(-1 + 4\sin^2\theta_W) + \gamma_5]e. \tag{12}$$

Then we can obtain the cross section. At the same length, the background events are at least 1000 times larger than the expected events at $1.0315 10^{-6}pa$. However, the situation can be remedied by careful analysis on kinematics.

The maximal differential cross sections of either $e^- + \tilde{\chi}_1^0 \to e^- + \tilde{\chi}_1^0$ or $e^- + n \to e^- + n$ occur near $\theta = \pi/2$. We have also the energy of the scattered electron E' as

$$E' = \frac{EM}{E(1 - \cos\theta) + M}, \tag{13}$$

where E is the beam energy and in the expression the mass of electron is ignored, M is the mass of either the SUSY particle or nucleon. Obviously, if $M \gg E$ we have $E' \sim E$, but as $E \sim M$, at $\theta = \pi/2$, $E' = ME/(M + E)$. In the BEPC case, if the electron is scattered from a SUSY particle, $E' \sim 2$ GeV, but when it is from the background nucleon, $E' \sim 0.6$ GeV. Therefore, if we set a reasonable cut at, say, 1 GeV for the kinetic energy of the scattered electron, we can effectively eliminate the background (the case for $\theta = 0$ vicinity should be excluded). However, if the beam energy is much greater than M, for example at LEP and future colliders, the energy difference of electron scattered from a heavy SUSY particle or a nucleon is negligible, so that one cannot distinguish the source of scattering and the expected events would be drowned in the ocean of background. Therefore, observation of SUSY dark matter via elastic scattering can only be feasible at low energy accelerator, and the energy of BEPC or charm-tau factory is ideal. Moreover, in that case, the mass difference of the neutral and charged SUSY particles has no effects at all.

It is noted that the main background is due to scattering between the beam electron and atmospheric neutron, since only neutron is neutral in the remanat atmosphere. In fact, the collision between beam electron and other charged particles in the atmosphere such as proton and electron can be easily determined by existence of trajectories of the bounced charged particles and the scattered beam electron. Therefore our signal can be clearly singled out from the background.

In summary, we have proposed a new method of detection of the cold dark matter and analyzed the possibility of observing inelastic scattering processes between beam particles and the ambient neutralino cold dark matter particles. We also investigate the situation for elastic scattering. Our results suggest that if the mass gap between the lightest SUSY particles $\tilde{\chi}_1^0$ and their corresponding charged SUSY particles $\tilde{\chi}_1^-$ is less than 1 GeV, the BEPC energy is enough to cause inelastic processes where the products can be easily identified in present experimental facilities. For large mass gap, one needs to invoke larger machines such as LEP etc.

Besides we also discuss the possibility of measuring elastic scattering and find that by carefully setting a kinematic cut for the scattered electron energy, it is possible to identify if they are scattered by the incident SUSY particles from large background at BEPC, but not at accelerators with higher energies.

Our conclusion is that using beam particles to bombard on the coming SUSY particles may cause inelastic and elastic processes whose products are measurable and can be identified.

We should point out that Errede and Luk in Ref.[13] have outlined a scheme for searching for terrestrial dark matter at Tevatron. However they have not studied in detail the processes of the beam particles colliding with heavy cold dark matter particles, such as the neutralino. As pointed out in this paper, the heaviness of the dark matter particles help identify the signals from the background.

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